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ABSTRACT

Due to titanium's excellent strength-to-weight ratio and high corrosion resistance, titanium and its alloys have great potential to reduce energy usage in vehicles through a reduction in vehicle mass. The mass of a road vehicle is directly related to its energy consumption through inertial requirements and tire rolling resistance losses. However, when considering the manufacture of titanium automotive components, the machinability is poor, thus increasing processing cost through a trade-off between extended cycle time (labor cost) or increased tool wear (tooling cost). This fact has classified titanium as a "difficult-to-machine" material and consequently, titanium has been traditionally used for application areas having a comparatively higher end product cost such as in aerospace applications, the automotive racing segment, etc., as opposed to the consumer automotive segment. Herein, the problems associated with processing titanium are discussed, and a review of cutting tool technologies is presented that contributes to improving the machinability of titanium alloys. Additionally, non-conventional machining techniques such as High Speed Machining and Ultrasonic Machining are also reviewed. Additional factors specific to machining titanium alloys are also discussed, a crucial one being its non-conformity with standard tool wear models. Subsequently, the results of a controlled milling experiment on Ti-6Al-4V are presented, to evaluate the relationship between tool preparation/process parameters and tool wear and for a comparison with traditional wear models.

INTRODUCTION

Titanium is the seventh most abundant metal and the fourth most abundant structural metal in earth's crust behind aluminum, iron and magnesium. Titanium and its alloys are considered as alternatives in many engineering applications due to their superior properties such as retained strength at elevated temperatures, high chemical inertness and resistance to oxidation. Titanium has traditionally been utilized as a lightweight, very strong and exceedingly corrosion resistant material in the aerospace industry, electric power plants, seawater desalination plants, and heat exchanges. Also, it has been used in industrial applications such as petroleum refining, nuclear waste storage, food processing, pulp and paper plants, and marine applications [1].

Nevertheless, when considering the use of titanium as an automotive component material, there are several conflicting aspects that must be addressed. First of all, the cost of titanium is relatively high in comparison to other common engineering materials such as aluminum, magnesium, and steel. For this reason, it specifically calls for implementation and use only when extreme conditions are to be met, such as in the aerospace industry.

The main reason for the increased cost is due to the limited demand from other market segments, thus making the extraction of the titanium ore expensive. Also, the processing cost for converting the ore into commercially usable titanium and its alloys is high. This requires special processing procedures and involves vast batch production and careful process control, making them difficult to automate. Second, the difficulty in efficiently manufacturing titanium components has a significant adverse effect on processing cost which is mainly due to its low modulus of elasticity and high yield stress. Another manufacturing concern that arises during the machining of titanium is its susceptibility to work hardening during the cutting process and its tendency to react with many cutting tool materials causing substantial tool wear. Additionally, titanium has poor thermal conductivity properties, making heat dissipation a problem, again contributing to higher tool wear.

Of primary concern however is the lack of material grade development outside the aerospace industry in which most of the alloys are developed for extreme conditions. This severely limits the currently available grades suited for automotive applications. Thus, a suite of lower strength alloys with properties specially catered for commercial automotive use needs to be developed.

This paper examines most of the issues traditionally associated with the machinability of titanium and titanium alloys. Some methodologies and techniques are recommended for mitigating the difficulties faced during titanium processing and its unique tool wear characteristics are analyzed. This study is expected to primarily assist in the reduction of the processing cost of titanium and its alloys for automotive component manufacture. This will help reduce the operating cost of a road vehicle in terms of better fuel economy due to the reduced mass, which in turn translates to better energy efficiency.

TITANIUM IN THE AUTOMOTIVE INDUSTRY

With the automotive industry constantly striving to reduce fuel consumption as well to lower emissions, there are two broad approaches that could be followed to attain these objectives. Either, the combustion process and other related aspects could be optimized for better fuel efficiency or the mass of the vehicle could be reduced as much as possible within limits. For the reduction in vehicle mass approach (by replacing heavier steel components with lightweight materials such as titanium), a fundamental total life cost model for energy reduction is presented which relates vehicle mass to energy consumption and hence emissions.

TOTAL LIFE COST MODEL - ENERGY REDUCTION

The tractive force supplied to propel the vehicle works to overcome three main resistive forces, namely: the rolling resistance of the tires due to material hysteretic loss, the aerodynamic force, and the inertial force due to the vehicle acceleration. This tractive force can be expressed as given in Eq. (1).

$$F_{tractive} = ma + \frac{1}{2} C_D \rho A_f v^2 + mgC_r \quad (1)$$

where, '$F_{tractive}$' is the tractive force at the tire-road interface, 'm' is the mass of the vehicle, 'a' is the forward acceleration of the vehicle, 'C_D' is the drag coefficient, 'ρ' is the density of air, 'A_f' is the vehicle frontal area, 'v' is the velocity of the vehicle, 'g' is the acceleration due to gravity and 'C_r' is the rolling resistance coefficient of the tires.

This equation can be further extended to a mass-energy relationship over standard driving cycles as in Eq. (2).

$$E = m\beta_1 + \frac{1}{2} C_d \rho A_f \beta_2 + mgC_r \beta_3 \ (2)$$

where, 'E' is the energy required at the tires for propelling the vehicle over a standard driving cycle, and 'β_1, β_2, β_3' are vehicle independent, but cycle dependent driving cycle constants for driving/braking, aerodynamic, and rolling resistance effects respectively.

Thus, on examining the relationship between the mass of a vehicle and its fuel consumption, it is observed that they are directly proportional to each other such that as the mass is increased, the inertial and rolling resistance effects become increasingly arduous to overcome and hence they increase the amount of energy required to propel the vehicle. With the requirement of more energy, fuel consumption increases and hence vehicle emissions.

It has been reported that a 1.0% decrease in vehicle mass would result in an approximate fuel efficiency increase of 0.7% [2]. On adding up such 'seemingly' insignificant numbers over the overall lifetime of a vehicle and multiplying it with the number of vehicles out on the road today (in the United States alone), it would translate into significant energy savings and reduced emissions, thus substantiating the fundamental motivation for this study.

OTHER MATERIAL ALTERNATIVES

When targeting the reduction of mass of automotive components by replacing heavier steel components with lightweight materials, there are a number of candidate materials that fit the requirements. Three of these common lightweight engineering materials include: aluminum, magnesium and titanium. Some of the most relevant material properties of these three materials are compared in Table 1 along with the properties of steel that is used in automotive components.

Table 1: Relevant material properties of lightweight automotive metals compared to steel [3]

Property	Steel	Aluminum	Magnesium	Titanium (pure)	Titanium (6Al-4V)
Density (kg/m3)	7850	2700	1810	4500	4500
Yield Strength (MPa)	230	350	140	435	900
Tensile Strength (MPa)	430	400	200	550	970
Strength to Weight Ratio	0.05	0.15	0.11	0.12	0.22

On comparing the properties of the different lightweight materials listed in Table 1, it it can be observed that titanium does not possess the lowest density among the materials, i.e., it is not the lightest among the three. However, its strength to weight ratio far exceeds those of the other materials. Ti-6Al-4V or Grade 5 titanium, which has a strength-to-weight ratio of 0.22, is the most commonly available commercial alloy and is used extensively in the aerospace industry. Additionally, titanium has high corrosion resistance, the highest melting point and the best high temperature stability characteristics (least coefficient of thermal expansion) out of the three. These reasons favor titanium as the best candidate replacement material among the three, for replacing steel components in the automobile.

TITANIUM IN THE RACING SEGMENT

Currently, the automotive racing industry has been reliant on titanium alloys in many of their vehicle components to improve performance (again, as a mass reduction factor). Some examples include: connecting rods, camshafts, valves, valve springs, suspension springs, wheels, hubs and exhaust systems. However, as mentioned earlier such extensive use as in the automotive racing segment has not carried over significantly to commercial automotive vehicle market, the main reason being the high costs associated with its processing. Yet, several automotive companies have explored the use of titanium components and have used them in their production vehicles. The first implementation was in the Acura NSX where titanium connecting rods were used [4]. Also, the 1998 Japanese car of the year, the Toyota Altezza, used titanium valves in its engine [4]. As another example, GM used Grade 2 titanium to produce their exhaust system for the 2001 Chevrolet Corvette Z06, saving approximately 7.6 kg [5].

CHALLENGES FOR INCORPORATING TITANIUM INTO AUTOMOBILES

For the future use of titanium as a competitive automotive component material, technologies need to be developed which can reduce the current high costs associated with its extraction and processing. Note that difficulty level of mining titanium ores is fairly similar to ores like bauxite or iron ore; the lower demand is the reason why titanium ores are costlier than those of aluminum or steel. Once the ore gets converted into pure metal its price increases considerably mainly due to the complex extraction process. Since the cost of the extraction process is a greater contributor to the total extraction cost than the cost of the metal ore itself, recent work has been pointed in the direction of reducing this cost by increasing the level of automation of the extraction process and by lowering the high energy requirements. The Armstrong Process, a hybrid of the standard Knoll Process, has recently been experimented with to increase the efficiency by making the Knoll Process semi-continuous [6-8]. However, it is unclear if this new process has caught on to a large scale production at the moment.

Since the introduction of titanium in the 50s, the demand and hence the cost of titanium has had a direct relation to the conditions and demands of the military and the commercial aerospace industry. Introduction into the commercial automotive market is expected to stabilize demand and prices. To mitigate the lack of development of titanium outside of the aerospace industry, possible alternatives being explored include the development of lower strength titanium alloys, process development, and process modeling and optimization.

The cost of finished titanium components are considerably larger compared to those made of aluminum or seteel. This is mainly attributed to the processing challenges of titanium, the reasons for which are detailed in the next section. Other studies have been conducted which propose net-shape forming of automotive components using casting followed by a machining process [9-10]. This is proposed to reduce the cost involved in machining automotive components using titanium.

TITANIUM MACHINABILITY

Machinability is considered as the ease with which a material can be machined and it is customary to speak of it as a material property. Although there is no physical quantity to rate the machinability, it can sometimes be quantified as a combination of the machinability index, chip formation characteristics, tool wear, cutting forces acting on the tool, material removal rates, achievable surface finish, etc. Usually good machinability translates to a combination of cutting with minimum energy, minimum tool wear, good surface finish, etc.

MACHINING ECONOMICS

The fundamental idea of machining economics is simply to obtain the lowest possible cost per part that is manufactured while maintaining the quality standards of the product. A fundamental cost model [23] for machining one part can be expressed as in Eq. (3).

$$C_p = C_m + C_s + C_l + C_t + C_{rm} \quad (3)$$

where, 'C_p' is the total cost per part, 'C_m' is the machining cost, 'C_s' is the setup cost, 'C_l' is the material handling cost, 'C_t' is the tooling cost and 'C_{rm}' is the raw material cost.

The machining cost 'C_m' is a function of cycle time, the setup cost 'C_s', a function of the number of tool changes per part and the tooling cost 'C_t', a function of the number of tool changes per part, tool change time, and tooling cost. A plot of the machining cost per part that is calculated for a typical machining scenario is depicted in Figure 1. Note that, the process of reducing the total cost per part by varying the cutting parameters (speed, feed, depth of cut, etc.) consists mainly of two conflicting factors: reduced cycle time and too many tool changes. An optimal cutting speed (V*) can be solved for analytically, however it is usually very unlikely that one would be able to include all the factors contributing to the cutting process.

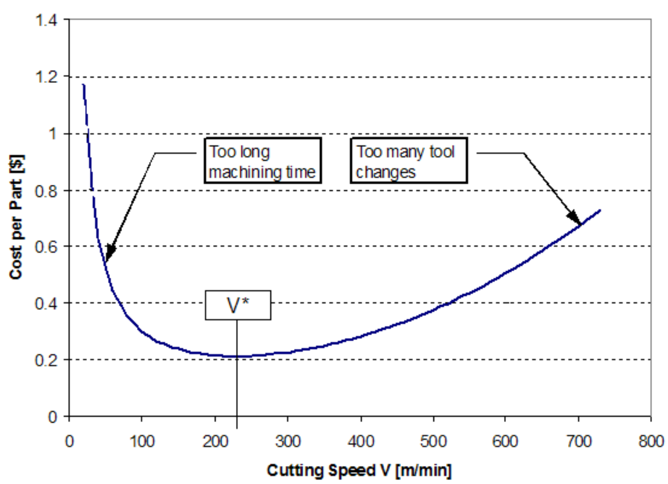

Figure 1: Machining cost/part for a typical machining scenario

This conflict between reduced cycle time and too many tool changes is especially pronounced in the case of machining titanium and its alloys. A high tool wear rate, common when machining titanium result in more number of tool changes pointing to a reduction in machining parameters (speed, feed, depth of cut, etc.), however, such an action will increase the cycle time and hence the cost per part.

ISSUES IN TITANIUM PROCESSING

The main adverse properties of titanium and its alloys that classify it as a “difficult-to-machine” material are summarized below:

Low Thermal Conductivity:

Due to the relatively low thermal conductivity of titanium, the majority of the heat generated during the cutting process is transferred to the cutting tool edge and tool face rather than to the chips or the workpiece. It has been reported that 80% of the heat of cutting is transferred to the tool when cutting titanium as compared to 50% when cutting steel [11]. This distribution is shown in Figure 2 for various tool materials (from left: Oxide ceramic, High-speed steel, Carbide P10, Stelit, Carbide K10, K20 and Diamond). As a result, the tool temperature becomes very high creating high thermal gradients which significantly affect the tool properties leading to rapid tool wear and even catastrophic failure.

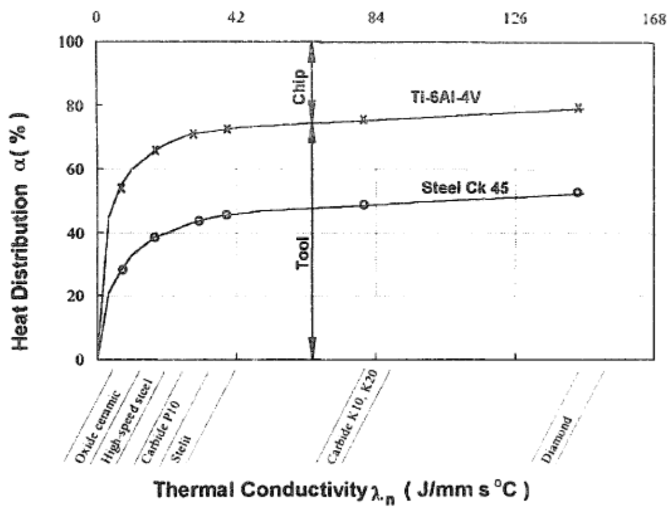

Figure 2: Comparison of heat distribution between chips and cutting tool for titanium and steel [11]

High Speed Steel (HSS) tools experience a loss of hardness at temperatures greater than 600° C. During titanium machining, this leads to severe plastic deformation of the tool. Cemented carbide and ceramic tools also experience plastic deformation leading to cracks by thermal shock. With tungsten carbide (WC/Co) tools, the high temperatures and high thermal gradients cause mechanical and cyclic stresses as well as adhesion of pieces of the titanium workpiece to the tool furthering flank wear [1].

Low Elastic Modulus:

The low elastic modulus of the titanium causes large deflection of the workpiece during machining. The deflections are twice that experienced with steel [1]. These large deflections cause chatter, vibration, rubbing with the tool and increase in temperature during machining [1] which in turn leads to poor surface finish.

High Chemical Reactivity:

The high chemical reactivity of titanium causes the workpiece to adhere to the tool which leads to chipping of the tool and eventually tool failure [1]. This alloying tendency is more pronounced at elevated temperatures often causing galling, welding, or smearing of the workpiece.

High Strength at Elevated Temperatures:

Though appearing to be a favorable property, titanium's tendency to maintain its strength at higher temperatures hinders chip formation. This leads to the formation of small chips which result in small contact areas between the tool tip and workpiece and hence higher stresses in the cutting zone [1]. It has been observed that these high stresses are a result of the small contact area (about $1/3^{rd}$ that of steel) and not due to an increase in forces. Though the forces and hence power requirement for machining titanium is lower than that of steel, titanium's lower thermal conductivity results in more rapid tool wear than steel. Their specific cutting energies are:

- Specific cutting energy of Steel: 2.7 Ws/mm^3 to 9.3 Ws/mm^3
- Specific cutting energy of Titanium: 3.0 Ws/mm^3 to 4.1 Ws/mm^3

Additionally, when machining titanium, a high shear angle is typically formed ahead of the cutting edge which leads to small segmented (saw-tooth) chips [12]. These segmented chips result in high cutting forces, high temperatures and very high stresses in the cutting zone.

CUTTING TOOL TECHNOLOGIES TO IMPROVE MACHINABILITY

In light of the previously mentioned properties of titanium that adversely affect its machinability, recent research on its improvement has mainly focused on the following four areas [1, 22]:

TOOL MATERIALS

Tooling materials that are less resistant to wear or failure has been the primary focus. The most important parameters when considering a tool material for titanium is that it must have a high hardness at elevated temperatures (hot hardness), high thermal conductivity to mitigate thermal gradients and shocks, a high chemical inertness with titanium, and a high compressive and shear strength. High Speed Steel (HSS) tools experience a loss of hardness at temperatures greater than 600° C, leading to severe plastic deformation of the tool and hence being ineffective for titanium machining [1]. Yet, in recent years, the development of new tool materials has increased dramatically with the addition of coated carbides, ceramics, cubic boron nitride (CBN), and polycrystalline diamond (PCD). However, ceramics have not found much success as they are poor thermal conductors, have relatively low fracture toughness and react aggressively with titanium [13]. Additionally, CBN and PCD materials show increased tool life, however, these tooling materials have not had great success as a result of their additionally high costs [14]. Also, it has been suggested that binderless CBN (BCBN) tools are the most functional material for machining titanium alloys. A BCBN tool is created without the traditional metal or ceramic binders which limit the bonding strength. Note however that this tooling material is expensive.

TOOL GEOMETRY

Different tooling geometries that could increase the machinability of titanium by reducing cutting forces and hence extending tool life have been investigated. In a study [1] using self-propelled rotary tools, it has been demonstrated that the rotary tool is more successful in removing heat from the cutting zone and lowering cutting forces. Rotary tools utilize circular discs which rotate and move in the main cutting and feed directions. Shown in Figure 3 is the cutting temperature variation for two different tools with various cutting speeds [15]. As can be observed from the figure, the cutting temperature is approximately a couple of hundred degrees (K) lesser for the rotary tool. Thus, rotary tools do provide viable means for increasing tool life; however, they have not gained much popularity as a result of their inability to machine complex geometries and their requirement for shallow cutting depths.

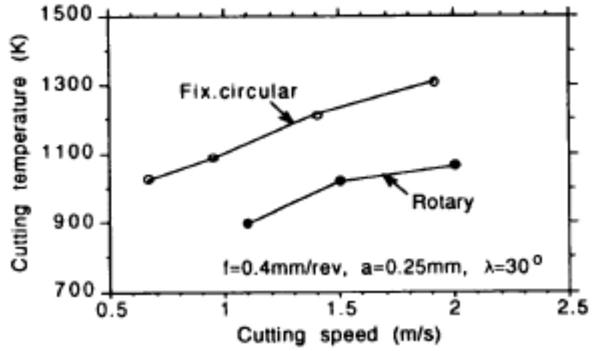

Figure 3: Cutting temperatures with varying cutting speeds for rotary inserts [15]

Additionally, ledge tools are an alternative that can be used for prolonging tool life. Ledge tools are constructed such that the cutting edge hangs out to the desired cutting depth and wears back along the length of the tool [1]. However, these tools are limited to straight cuts in operations such as turning, facing, and boring.

Another common practice for increasing tool life is to chamfer the cutting edge, thus reducing the propensity of tool tip chipping (edge preparation). This is derived from an old machinist practice of applying a diamond edge stone to the edge of the cutting tip. This chamfer helps to reduce chipping, thereby extending tool life, however it decreases tool performance as well. It usually creates a plowing effect on the workpiece and changes chip direction leading to crater wear mostly. A recent development called Engineered Micro-Geometry utilizes a defined shaped round edge instead of the chamfer to protect the edge of the tool. With this tool geometry, the negative aspects of chamfering are not encountered, yet it has been proven to protect against normal edge failure [32].

PROCESS PARAMETERS

For the identification of optimal process parameters for the cutting conditions at hand, numerous studies have examined different combinations of cutting feeds, speeds and depth of cuts. It has been reported that cutting speeds have the most substantial affect on tool life [16]. This is depicted in Figure 4, where it can be observed that tool life is greatly reduced at higher tool speeds when machining Ti-6Al-4V using a carbide tool. Additionally, it has been ascertained that the feed rate also has a significant effect on the life of a tool when machining titanium or its alloys. The decrease in tool life is reported to vary exponentially as the cutting feed increases [1]. This effect can also be observed from Figure 4, for a given cutting speed. Also, as would be expected, with an increasing cutting depth, the tool life decreases rapidly when machining titanium.

A general recommendation of startup values for the approximate range of cutting parameters for milling operations on titanium alloys is as follows [23]: For carbide or diamond cutting tools, recommended cutting speeds are 40-150 m/min for a depth of cut of 1-8 mm and feed/tooth of 0 .08-0.46 mm/rev.

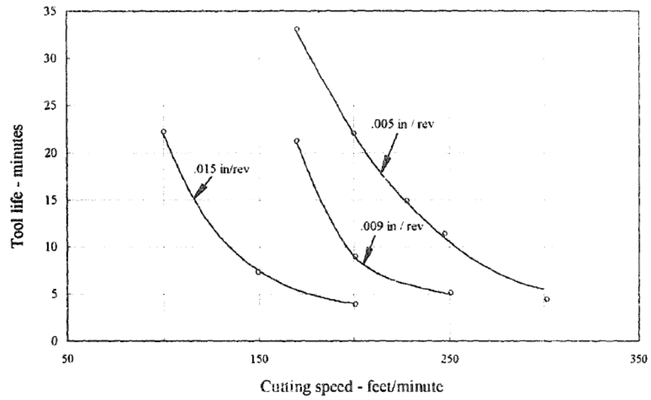

Figure 4: Tool life variation with cutting feeds and speeds [16]

Additional work involving the development of elaborate machining models for titanium have been conducted, generating both extended analytic material property based models as well as FE models. A better understanding of the titanium cutting process and chip formation has been explored through these studies. One of the resulting studies includes a model that is capable of predicting chip morphology as well as cutting forces for titanium machining [17, 18].

CUTTING FLUIDS

As a result of the high temperatures encountered during the cutting process as well as the tendency for welding of chips to the tool, the use of coolant during the cutting process helps to alleviate these problems while increasing tool life. A plentiful amount of coolant will allow for good chip removal as well as a reduction in the thermal gradients present [1]. One particular study examined various cooling methods and discovered that a compressed cold nitrogen gas and oil mist provided the best extended tool life while milling Ti-6Al-4V with a coated cemented carbide tool [19]. Also, it was noted in one particular study that the addition of liquid nitrogen cooling through a micro-nozzle could produce increased tool life up to five times greater than current emulsion cooling [20]. Another technique used to enhance tool life when machining is to use high pressure coolant. The addition of the coolant aids in lowering the tool temperature and also aids in reducing the welding of chips to the tool since the high pressure flow aids in creating discontinuous chips [21].

NON-CONVENTIONAL MACHINING TECHNIQUES

There are additional non-conventional machining processes that are expected to improve the machinability of titanium and its alloys. These include techniques such as High Speed Machining (HSM) and Ultrasonic Machining (USM).

HIGH SPEED MACHINING

The productivity of a machining operation may be increased by incorporating a larger depth of cut, a greater feed rate or a faster cutting speed. However, an increased depth of cut or an increased feed rate usually results in larger cutting forces as well as a poorer surface quality. Hence, using a faster cutting speed turns out to be the most economical parameter increment and is defined as High Speed Machining (HSM). HSM is most commonly 5 to 10 times the normal cutting speed of conventional cutting [22]. The range of cutting speeds for conventional and HSM of some standard metal alloys and plastics is depicted in Figure 5.

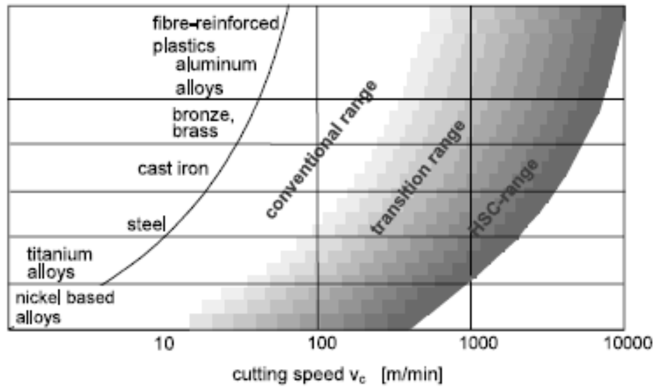

Figure 5: Comparison of cutting speeds for conventional and HSM for various materials [22]

Not only does HSM provide better productivity, but it also usually results in a better surface finish as well as improved dimensional accuracy. Moreover, this process reduces the amount of burring while also allowing for stress free components as a consequence of the reduced heat generation during the cutting process. Additionally, by employing this process, machining of thin-walled workpieces can be accomplished as a result of the decreased cutting forces, which would not be otherwise possible in conventional machining.

Currently, HSM has been very successfully incorporated for the machining of aluminum alloys and is being investigated as a viable high productivity method for titanium alloys. For aluminum alloys and most other materials, the maximum cutting temperature reached during machining is much lower than those during conventional machining. However, this is not true for the case of titanium and its alloys [22]. As a result, the tooling capabilities once again limit the high productivity titanium machining, even at these elevated speeds. Advanced tool insert materials such as CBN and PCD have had some success, however, these materials still have limited tool life due to the high stresses and elevated temperatures at the cutting region [22]. Presently, research on HSM of Ti-6Al-4V suggests that BCBN tools are the most effective tool material for machining titanium and its alloys at high cutting speeds [14]. Note however that these advanced tooling materials increase the cost of the overall process while improving machining efficiency.

ULTRASONIC MACHINING

Mostly for the creation of holes and cavities in brittle or difficult-to-machine materials, Ultrasonic Machining (USM) is commonly used. This process basically turns electrical energy into mechanical vibrations such that a tool and abrasive slurry remove material by micro-chipping or erosion [23]. With this process, there is no deformation of the workpiece and excellent surface finish characteristics can be achieved. Also, USM does not thermally damage the workpiece and does not leave any residual stresses as other non-conventional processes (i.e. laser beam cutting or electrical discharge machining (EDM)). However, this process is limited by the material removal rate which is low in comparison to other processes. Conversely, a study using a combination procedure of EDM and USM is able to increase the material removal rate compared to traditional USM or EDM alone [24]. A more recent study was conducted which specifically examined USM of Grade 1 titanium [25]. In this study, the relationship between the material removal rate and tool wear rate was examined by varying factors such as the tool material, abrasive slurry grit size, and the power rating of the machine. It was concluded that all three factors have a significant impact on the material removal rate, tool wear rate, and final surface finish.

Figure 6 shows the surface of an ultrasonically machined titanium sample which exhibits a non-directional surface texture when compared with a conventionally machined surface [26].

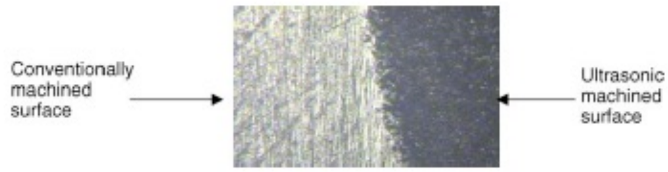

Figure 6: Machined surface showing comparison of conventional machining and USM at 100X [26]

ADDITIONAL CONSIDERATIONS FOR IMPROVING MACHINABILITY

The suggestions for improving the machinability of titanium and its alloys that were provided in a previous section were grouped under the four main sub-headings of tool materials, tool geometries, process parameters and cutting fluids. These main research areas for possible machinability improvement are applicable to most standard automotive and engineering metals, and not exclusively to titanium. In this section however, a number of additional factors are addressed that are exclusively catered for contributing to the improvement of machinability of titanium and its alloys.

DEVELOPMENT OF LOWER GRADES

New grades of titanium alloys that better cater to the cost and performance requirements of the automotive industry need to be developed. Developing a suite of lower strength titanium alloys with lower performance properties than those required by the aerospace industry, will have the combined benefits of lower material cost as well as time/cost savings due to easier processing. These two factors are directly tied in with improving the machinability of titanium to a considerable extent. Moreover, the availability of suitable grades for multiple automotive applications will increase the demand of titanium, which will in turn further reduce the cost.

MACHINING STRATEGY

In contrast to the well documented machining strategies for aluminum and steel, machining strategies for titanium and its alloys should be adopted with care. An initial production planning process consisting of feature assessments, machining plans as well as cutter and tool selections is strongly recommended rather than proceeding instinctively with standard cutting parameters.

The life of a cutting tool used for machining titanium and its alloys depends heavily on the cutting speed due to the high temperatures generated at the tool face and cutting edge. For machining titanium, it is advised to use lower cutting speeds and higher feeds. Additionally, to reduce cutting forces and tool wear, tools inserts with sharp edges, small tool nose radius and high positive rake angles to reduce friction are often recommended for titanium milling [27]. Once a sharp, more acute edge begins to break down, wear propagates more rapidly than in a blunter, negative tool.

A good resource for specific recommendations on achieving good machinability can be obtained from tooling manufacturers. Some of their recommendations specifically pertaining to titanium include, but are not limited to [27]:

- Medium/high pressure coolant (1000 psi) applied through the spindle and externally, showing benefits for machinability.
- Range of recommended cutting speeds, feeds, spindle specifications, etc., for different titanium alloys.
- Improvement of tool life and feed capability for low approach angle (round) inserts.

- Specific limits on surface cutting speeds for roughing and finishing operations.
- The optimum cutter diameter to width of cut ratio (very important).
- Selection of cutter and insert types, machine, power and geometric requirements as well as recommended start cutting data.

In certain instances, it would be beneficial to adopt a combination of newer machining (milling) techniques/concepts for increased machinability compared to traditionally followed tool paths for plunging, slotting, pocket milling, roughing, profiling, etc. Some examples of such suggestions include [28]: Slice milling techniques, Roll-in methods, Angle cutting, Straight and Helical ramping, Circular and Helical interpolation, Trochoidal Milling, etc. A combination of these techniques was employed to demonstrate the improved machinability characteristics (cycle time, surface finish, lesser number of tool changes) of common materials via a live demonstration at a machine tool facility in 2009.

TOOL WEAR MEASUREMENT

The accurate prediction of tool life during a manufacturing process is important for the design of cutting tools and machining processes. The traditional method of measuring tool wear and hence predicting tool life via the Taylor's equation holds reasonably well for a number of common automotive and engineering metals, however, it doesn't for titanium. The ability to predict tool life for a particular machining process involving titanium is essential for the optimum selection of machining parameters and tooling. This sub-section serves to highlight this fact by comparing the tool wear results obtained through two methods for a controlled milling experiment.

<u>Traditional Tool Wear Characterization:</u>

For typical milling operations, the end of tool life is often reported as a measure of the quantity of wear on the flank and crater faces of a tool insert. In particular, wear is characterized as a measure of the flank depth (VB) or crater depth (KT) as shown in Figure 7.

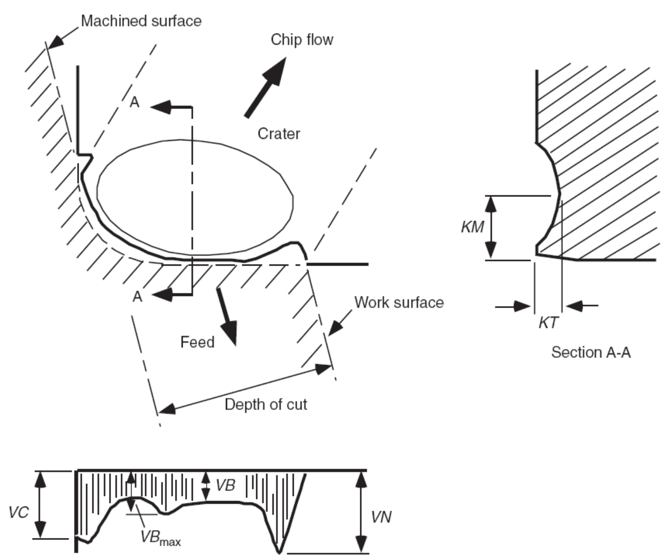

Figure 7: Flank and Crater wear measurements [29]

The standard measure for the end of tool life for carbide tools is a uniform average flank depth over all the teeth of 0.3 mm or a localized wear depth of 0.6 mm, according to ISO 8688-2 [31].

The fundamental cutting tool wear model used to predict tool life is the Taylor's tool life relation as given in Eq. (4). It relates usable life 'T' in minutes to the cutting speed 'V' while 'n' and 'C' are process-specific empirical constants.

$$VT^n = C \quad (4)$$

<u>Non-validity of traditional tool wear models for titanium:</u>

Tool wear, particularly flank wear (VB) is used as a common tool life criterion as it is easy to determine quantitatively and since it has significant influences on workpiece surface roughness and accuracy. The Taylor's tool life model has been shown to have reasonable agreement for a wide range of standard cutting processes. For standard machining processes, there is usually a short initial breakdown phase, followed by a long uniform wear rate phase until a final rapid breakdown occurs signaling complete tool failure.

However, for titanium milling, the tool wear does not seem to exhibit a linear constant wear rate phase and catastrophic tool failure can occur without warning. Thus, the Taylor's tool life model does not hold for titanium machining. To further elaborate this point, the results of a controlled milling experiment on Ti-6Al-4V is presented and the tool wear results obtained through two methods are compared.

<u>Experimental Setup and Results [30]:</u>

A milling experiment on a Ti-6Al-4V workpiece was conducted at two levels of feeds and speeds as listed in Table 2. The depth-of-cut was held constant at 2.0 mm. No coolant was used for these experiments. The experiments were performed on an OKUMA MB-46VAE 3-axis vertical milling center. Carbide inserts with (PVD) TiAlN coating were used. A tool holder measured 1 inch diameter and could hold up to four indexable inserts. All four inserts were used in the tool holder for each experiment in Table 2. The inserts had a 28° positive rake angle.

Table 2: Experimental design setup

Experiment Number	Speed (m/min)	Feed (mm/rev)
1	200	0.5
2	200	0.2
3	70	0.5
4	70	0.2

Each milling pass was a shoulder cut 12.7 mm wide and 154.8 mm long. The flank wear of each insert was recorded four times for each experiment, once before machining and after each of three milling passes of 154.8 mm each. Therefore, each insert was eventually used for a total cut length of 464.4 mm. The measurements were recorded with the Zygo NewView 7200 white light laser interferometer. A fixture was used to hold the insert in place on the interferometer's stage. Additionally, a stereo-microscope was used to capture actual images of the insert for wear mechanism analysis at 40X. The flank wear measurements are shown in Figure 8.

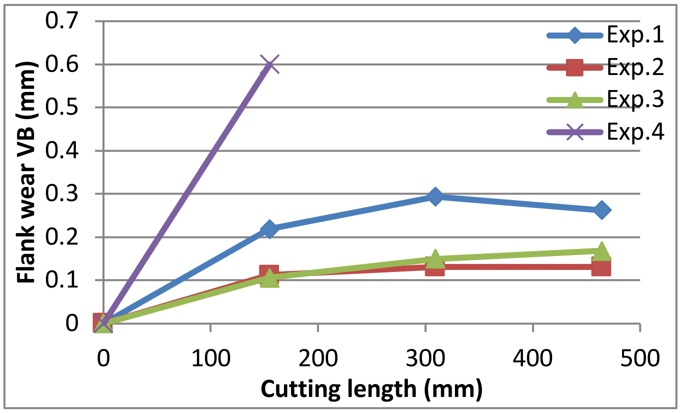

Figure 8: Measured flank wear (VB) values

Note that experimental setup 4 experienced a catastrophic insert failure within the first run step and hence its data values have been truncated.

<u>Volumetric Tool Wear Characterization [30]:</u>

It is suggested that the traditional tool life characterization shown in Figure 7 does not sufficiently capture tool wear. It is believed that wear can be more accurately characterized for modeling purposes by a volumetric quantification. The procedure as elaborated in [30], characterizes complex milling tool geometry profiles, and volumetrically quantifies tool wear data obtained via the titanium cutting experiment to ascertain the progression of volumetric wear using this new measurement approach. A normalized average volumetric wear values for the same experiment is shown in Figure 9. Also shown in Figure 10 are the absolute values of the volumetric wear measurements.

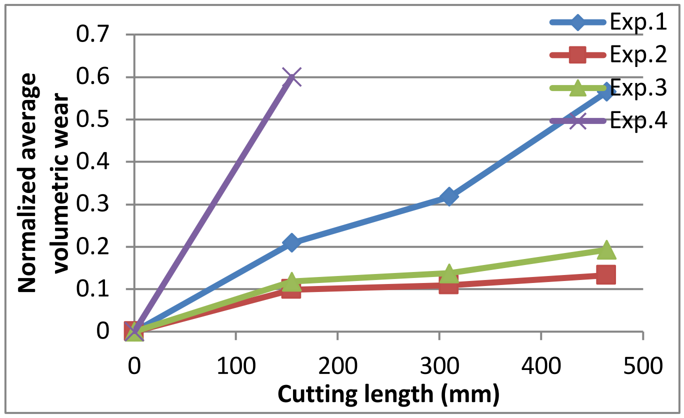

Figure 9: Normalized average volumetric wear data

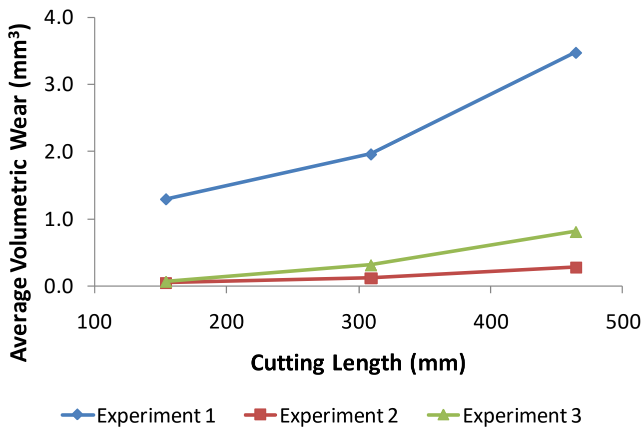

Figure 10: Absolute volumetric wear data in cubic millimeter

<u>Comparison of Results:</u>

On comparing the tool wear data results from the two methods employed: i.e., traditional flank wear measurement and the volumetric quantification of tool wear, certain conflicting results can be observed. For instance, for the experimental setup 1 (200 m/min, 0.5 mm/rev), the flank wear values at cutting lengths of 316.8 mm (step-2) and 464.4 mm (step-3) can be observed to be fairly close to the flank wear value at 154.8 mm (step-1) (Figure 8), suggesting that the wear profile at the end of all these three steps are fairly similar in terms of flank land profiles. However, from the volumetric tool wear results (Figure 9), the relative wear at the end of step-2 and step-3 compared to the wear at the end of step-1 is considerably large (almost 2 to 3 times).

Figure 11-13 depict the microscope images of the flank land of the tool inserts captured at 40X for this experimental setup.

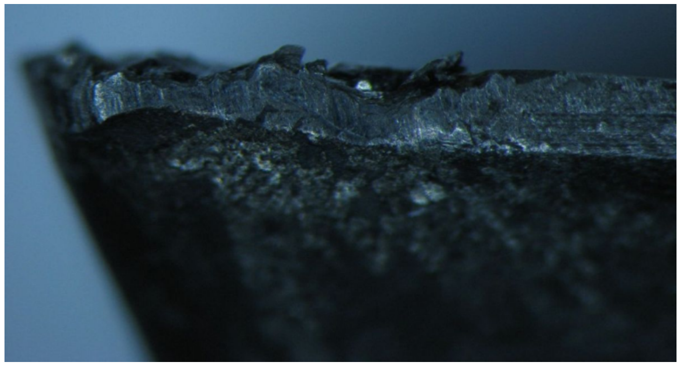

Figure 11: Flank land after 154.8 mm travel

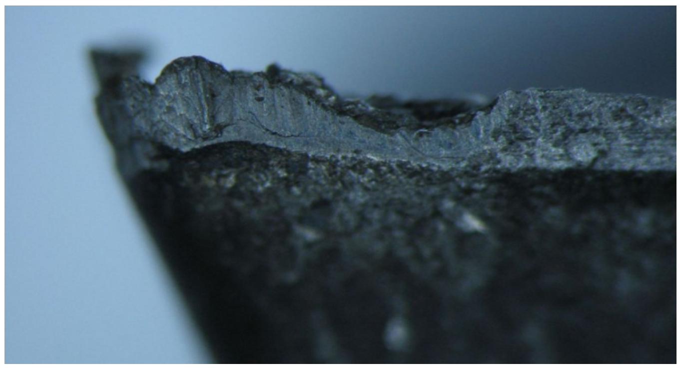

Figure 12: Flank land after 316.8 mm travel

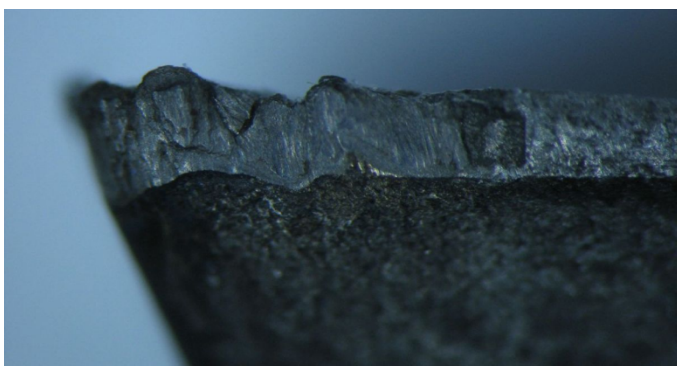

Figure 13: Flank land after 464.4 mm travel

On closely examining the microscope images, it can be observed that there is considerable difference in the wear levels between step-1 compared to step-2 and step-3. This effect has been more accurately captured by the volumetric quantification of tool wear method as can be seen in Figure 9. However, though the tool has worn out more, this progression of wear has not been captured by the traditional flank wear measurement method mainly because it measures a linear quantity (VB). Thus, it is suggested that the volumetric quantification method is a more accurate representation of tool wear as it takes into account multiple aspects of tool wear.

Relevance of volumetric wear method to titanium:

Using this new method, one is able to more accurately quantify tool wear as well as take into account additional standard tool wear parameters that could not be considered otherwise, with just a simple flank wear length measurement. Rapid tool wear is one of the most severe adverse aspects related to the machining of titanium alloys. An accurate measurement of tool wear (volumetrically) facilitates the availability of more accurate (empirical) model of titanium behavior during machining. This helps in predicting more optimal processing parameters for the machining of titanium and its alloys. This increases the machinability of the proposed titanium automotive component which in turn translates to a reduction in mass, fuel consumption, and hence energy.

Thus, in addition to reviewing the issues related to the machinability of titanium alloys and suggesting techniques for mitigating them, this paper also serves to validate the effectiveness of the new method for volumetrically characterizing tool wear elaborated in [30] over a traditional tool wear quantification. As is observed from the milling experiment results, the wear behavior of titanium alloys which does not follow the traditional Taylor's tool life model is more accurately characterized by this method.

CONCLUSION

This paper investigated aspects related to the machining of titanium and its alloys particularly for lightweight automotive use; the motivation for which was substantiated through fundamental cost models. The common issues encountered during titanium machining as well as standard and evolving techniques for improving machinability were discussed. Additionally, non-conventional machining techniques and strategies specific to improving titanium processability were proposed. Requiring special mention among these, are the results from a controlled milling experiment on Grade 5 titanium, which introduced a more accurate method for quantifying tool wear (volumetrically) which was able to capture the effects of multiple standard tool wear parameters rather than just flank wear measurements. These techniques for improving titanium machinability along with the introduced tool wear characterization method contribute to the reduction in the processing cost of titanium alloys for automotive component manufacture.

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